

# Nonlinear Estimation and Control of Particle Trajectories in the Ocean

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## LONG-TERM GOALS

Our long-range goal is to develop optimization methods: 1) to estimate the physical state of the ocean in order to understand the present and future conditions and associated variability/uncertainty, and 2) to utilize such forecast information for control-decisions such as optimal drifter deployment strategy. This is being accomplished through the use of data assimilation methods for ocean circulation models and the study of extending the assimilation formulation to an optimal control problem.

## OBJECTIVES

In this effort, we study application of the particle filter to the ocean dynamics and data assimilation, and application of the control theory to formulate a solution methodology to the optimal drifter deployment problem.

## APPROACH

We apply theories of dynamic systems, estimation, and control to: (i) optimally estimate the ocean currents that steer the drifters, (ii) determine the optimal initial location(s) to deploy drifters in order to reach a desired target location. To apply these theories, issues unique to ocean circulation and drifter trajectory must be addressed, and these are: incomplete state information, nonlinearity, and sub-grid (turbulent) scale parameterization. To address these issues: 1) an established data assimilation method (*reduced order information filter*, or ROIF) will be enhanced to incorporate drifter trajectory data; 2) the *particle filter* technique, a Monte Carlo method suitable for nonlinear/non-Gaussian dynamics, will be employed to track drifter trajectory and to formulate the optimal control problem; 3) an *observation system simulation experiment* (OSSE) will be conducted, using regional and basin-scale ocean circulation models, to determine if assimilation of drifter tracks can more realistically affect the submeso-and subgrid-scale processes.

## WORK COMPLETED (year one)

1) Majority of coding for the EnROIF assimilation system, a Monte-Carlo (or ensemble-based) enhancements to the existing ROIF method (Chin et al 2002), is complete and is in tuning stage for the 1/12-degree resolution Gulf of Mexico model. The co-PI A.Srinivasan has presented our twin-experiment result at a HYCOM Consortium Meeting held at NRL Stennis in April, 2007.

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- 2) A systematic approach to project assimilated information along the vertical axis is proposed for a hybrid coordinate ocean model which employs depth, density, and terrain-following (“sigma”) coordinates along the vertical. Preliminary results are presented at the Layered Ocean Modeling Workshop in August, 2007.
- 3) Behaviors of particle filter and smoother are studied using the chaotic tri-variate dynamics by Lorenz (1963), where the roles of dynamic regimes in effectiveness of the backward smoother (Chin et al 2007) are investigated (Figure 1) in order to apply the techniques in realistic ocean models.
- 4) A “source estimation problem” (see RESULTS, below) is being formulated in collaboration with Prof. A. Mariano, an ONR-sponsored collaborator at RSMAS/U.Miami, based on an actual scenario of drifting fisherman’s boat in Gulf of Mexico. Benefit of the particle filter method for this problem has been observed in a preliminary work.

## RESULTS

A central issue in optimal deployment of drifting sensors is: given a set of drifting sensors, and some estimate of the ocean currents and the wind, to determine the initial locations and times to release the drifters so that they would be transported to form a certain configuration at a later time. The “later time” can certainly not be too far into the future because of the chaotic nature of Lagrangian trajectories. Also, given the stochastic nature of ocean currents and winds, one can only solve this problem in a statistical sense. In particular, it is impossible to find a single solution to this problem, but a set of possible starting locations could be robust enough for practice. We will call this problem the “source estimation” problem.

In collaboration with Prof. Mariano, a following actual scenario is considered as a test case for the source estimation problem. In 1999, a fishing vessel was found drifting with all crew members dead, presumably by an accident, in Gulf of Mexico. It was necessary to determine the location and time of the accident, given that the ship started drifting some time after the last contact with a crew which took place approximately 5 days prior. The initial location of ship (at the time of the accident) can be traced back by inverse particle simulations based on available data on ambient surface ocean current and wind, as well as stochastic models of particle dispersion to represent turbulent variability in the current and wind. The drift brought about by the wind, or leeway motion, is quite sensitive to the vessel’s initial orientation relative to the wind direction, left or right of downwind. As the initial orientation is essentially unpredictable, we assign equal probability to the two outcomes, or a bi-modal statistical distribution.

We have compared three methods to estimate the likely initial location: (A) brute force search where an ensemble of 20 forward simulations were initialized at each of  $401 \times 401 \times 73$  space-time grid-points with a resolution of  $0.1^\circ \times 0.1^\circ \times 1\text{-hour}$ ; (B) ensemble of 1000 backward simulations that initiate a particle trajectory from the known final position backward in time, where 73 sets of different durations were used due to unknown initial time; (C) the same backward simulations as method B, except that a particle filter is applied hourly to each ensemble in order to give lower weights to outlying particles with respect to the instantaneous ensemble mean. These three methods have been repeated for each of the two values used for the leeway motion (cross-wind drag coefficient).

The particle filter used in the backward simulations (method C) is found to make useful contributions that it preserves bi-modal nature in the particle distribution and that it can focus the solution space into

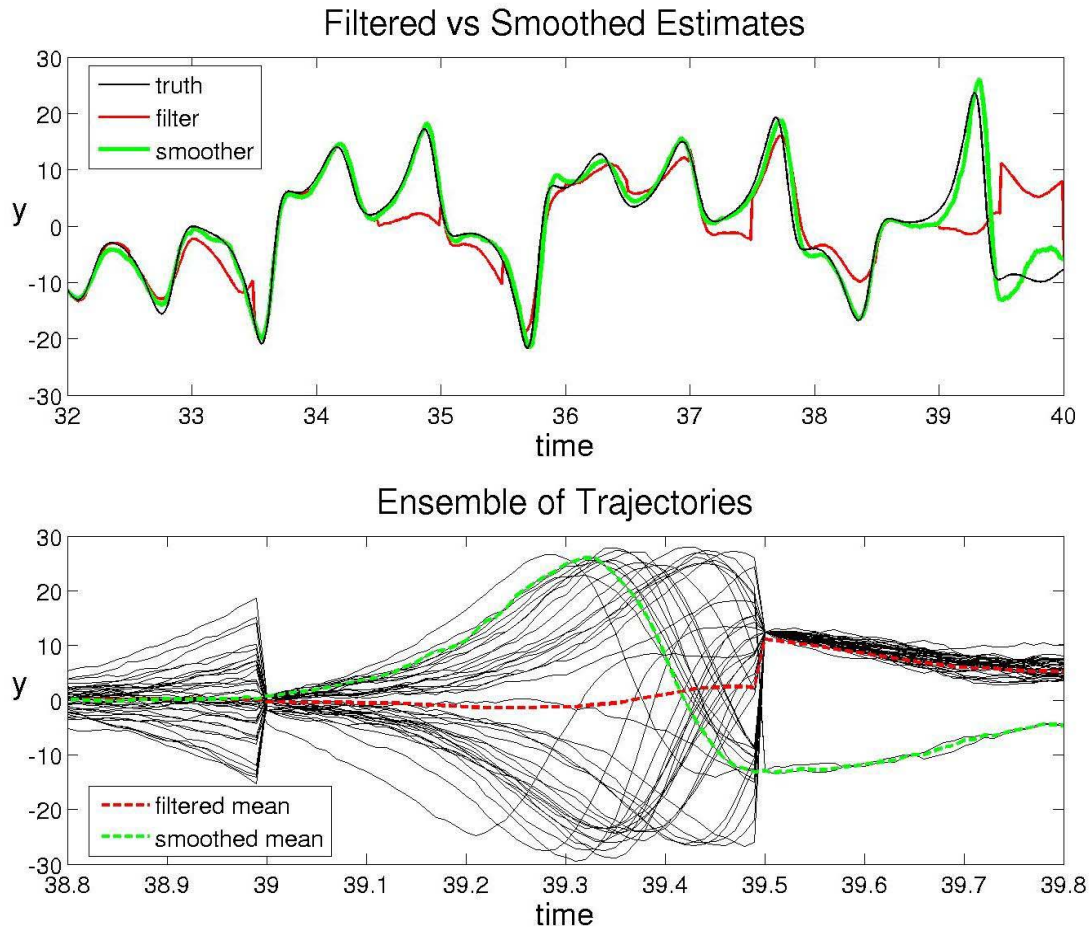
several “hot spots” rather one diffuse distribution. Figure 2 shows the most likely initial locations based on the brute-force search method A (blue marks, the same in both panels), where the use of either of the two leeway drag coefficient values clearly leads to a bi-modal distribution (symbols “×” or “o”). The black contours in the top panel is the probability density, at a contour interval of 0.05 per square-degrees, for the initial location due to the entire ensemble of unfiltered backward simulations of method B. The contours in the bottom panel, on the other hand, is the probability density due to the particle-filtered ensemble of method C. The distribution by method C has a bi-modal structure and agrees with the most likely locations estimated by the brute-force approach (method A) much better than the unfiltered distribution by method B. The number of trajectory simulation used is approximately 150 thousands for the result with method C, while it is nearly 500 millions for the case with method A, implying a computational advantage for using a method based on backward trajectory simulations.

## IMPACT/APPLICATIONS

The objectives of the project serve the ONR thrust area on Prediction Systems (improved now-casting and forecasting of ocean and coastal circulations through data assimilation) as well as Sub-Mesoscale Processes and Parameterization (through incorporation of drifting buoy data). The project addresses specifically the recent Department Research Initiative of Optimal Deployment of Drifting Acoustic Sensors (ODDAS). Also, the project contains a task directed at enhancing the capability of the *reduced order information filter* (ROIF), an ONR-sponsored assimilation system for layered ocean general circulation models including the MICOM and HYCOM.

## TRANSITIONS

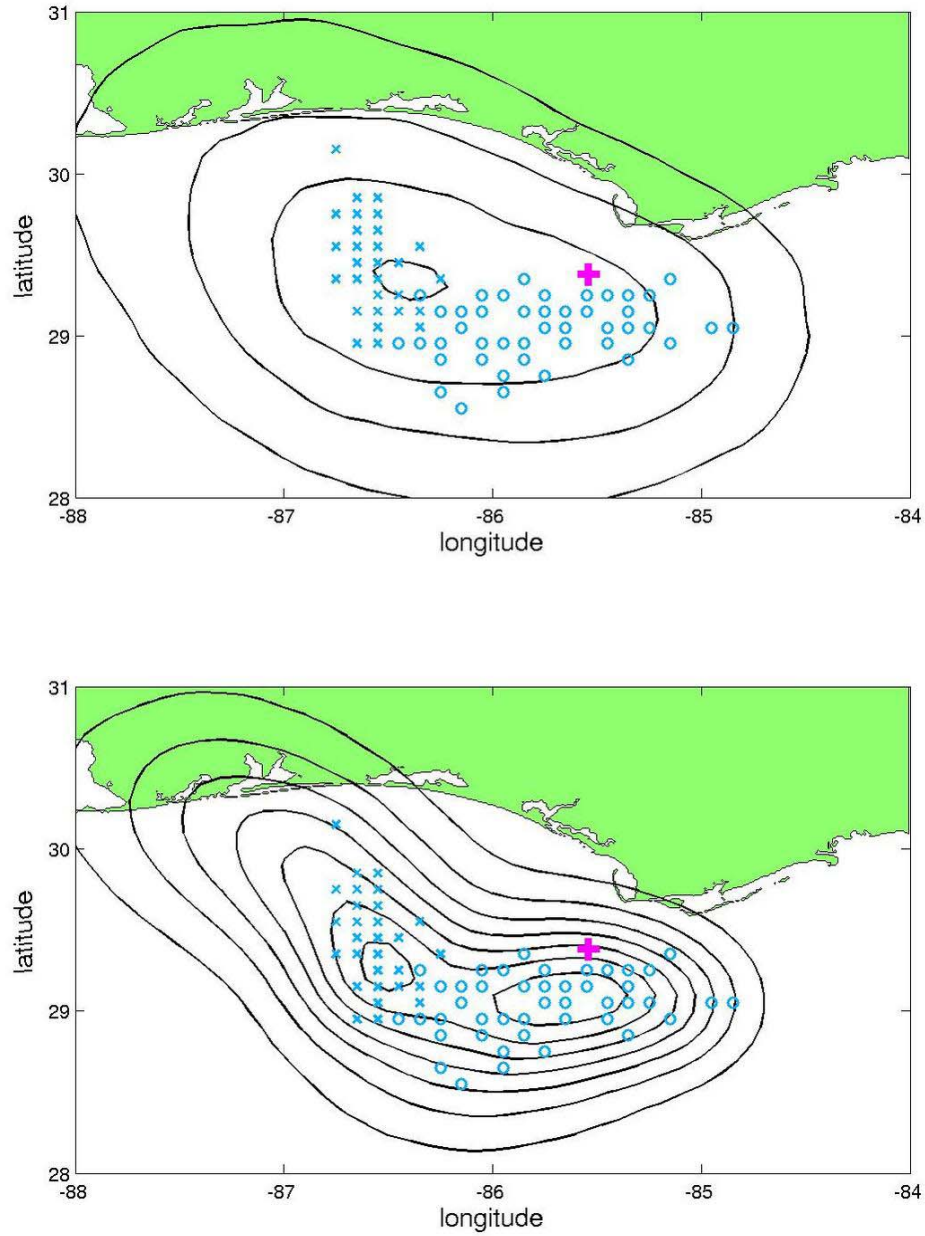
The Reduced Order Information Filter (ROIF) assimilation scheme, and its Monte Carlo version EnROIF, are being incorporated into the Hybrid Coordinate Ocean Model (HYCOM). Hindcast simulations with surface altimetry and temperature data assimilated are under development for a 1/12-degree resolution Gulf of Mexico domain and also planned for the Indian Ocean, for various scientific studies that require transport data.



**Figure 1.** *The particle smoother (green line) out-performs the particle filter (red line) when they are applied to the tri-variate dynamics of Lorenz (1963), where a reference trajectory (black line) is sampled every 0.5 time-unit and then assimilated into only the x and z variables by either the filter or smoother. The y-component of the trajectories are shown (top panel). The bottom panel is a close-up of all 40 members of the ensemble used, where the smoothing algorithm is shown to give more weights to the dynamically more consistent ensemble members (even when they exhibit less popular trajectories), compared to the filter which produces a simple un-weighted ensemble mean.*

## RELATED PROJECTS

U.S. GODAE: Global Ocean Prediction with the Hybrid Coordinate Ocean Model (HYCOM), in collaboration with the HYCOM Consortium (<http://hycom.rsmas.miami.edu>) where this project would improve the assimilation capability of HYCOM particularly for the drifting buoy data type.



**Figure 2.** *Contours of probability density (at 0.05 per square-degrees interval) of the initial position of the drifting fishing boat, using an ensemble of backward simulations (top) and a similar ensemble constrained hourly with a particle filter (bottom). The red cross is the final location of the boat after 2 to 5 days of drifting. Blue marks are estimates of the initial position using a brute-force simulations (see text), where different marks (x or o) indicate the two values used for the cross-wind leeway drag coefficient. The filtered ensemble agrees better with the brute-force solution, in terms of both localization and bi-modality.*

## REFERENCES

Lorenz EN. Deterministic nonperiodic flow. *Journal of Atmospheric Science* 20: 130-141, 1963.

Chin TM, Haza AC, Mariano AJ. A reduced-order information filter for multi-layer shallow water models: profiling and assimilation of sea surface height. *Journal of Atmospheric and Oceanic Technology* 19: 517-533, 2002.

## PUBLICATIONS (2007)

Chin TM, Turmon MJ, Jewell JB, Ghil M. An ensemble-based smoother with retrospectively updated weights for highly nonlinear systems. *Monthly Weather Review* 135: 186-202, 2007.

Chin TM, Ide K, Jones CKRT, Kuznetsov L, Mariano AJ. Dynamic consistency and Lagrangian data in oceanography: mapping, assimilation, and optimization schemes. in *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, eds: Griffa A, Kirwan AD, Mariano AJ, Ozgokmen TM, Rossby T. Cambridge University Press, 2007.

Chin TM, Ozgokmen TM, Mariano AJ. Empirical and stochastic formulations of western boundary conditions. *Ocean Modelling* 17: 219-238, 2007.

Haza AC, Mariano AJ, Chin TM, Olson DB. The mean flow and variability of the Gulf Stream-Slopeswater system from MICOM. *Ocean Modelling* 17: 239-276, 2007.

Molcard A, Ozgokmen TM, Griffa A, Piterbarg LI, Chin TM. Lagrangian data assimilation in ocean general circulation models. in *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, eds: Griffa A, Kirwan AD, Mariano AJ, Ozgokmen TM, Rossby T. Cambridge University Press, 2007.

Marcus S, Kim J, Chin TM, Danielson D, Laber J. Influence of GPS precipitable water vapor retrievals on quantitative precipitation forecasting in Southern California. *Journal of Applied Meteorology and Climatology*, accepted, 2007.

Dickey JO, Marcus SL, Chin TM. Thermal wind forcing and atmospheric angular momentum: Origin of the Earth's delayed response to ENSO. *Geophysical Research Letters*, 34, L17803, doi:10.1029/2007GL030846, 2007.